Numerical Process Studies of Continuum Internal Wave Dynamics: steady-state spectral and downscale energy transports

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LONG-TERM GOALS

To develop parameterizations of internal-wave driven turbulent mixing in a coastal environment suitable for use in regional numerical models.

OBJECTIVES

1. To investigate the dependence of coastal diapycnal mixing on aspects of low-mode, low-frequency internal waves that may feasibly be resolved by a regional numerical model, including:
   - internal wave frequency (generally tidal or wind-generated near-inertial waves)
   - vertical wave structure
   - wave strength
   - latitude (some wave instabilities are strongly latitude dependent)
2. To test the underlying assumptions and kinematic scalings of various proposed coastal mixing parameterizations, including KPP, the Gregg-Henyey scaling [*Gregg*, 1989], the scaling proposed by *D'Asaro and Lien* [2000], and the MacKinnon-Gregg scaling [*MacKinnon and Gregg*, 2003]

APPROACH

Away from surface and bottom boundary layers turbulent mixing is primarily driven by breaking internal waves. While internal wave energy is generated mostly in the form of large-scale waves (typically internal tides), it is the smallest-scale internal waves that break through shear or convective instabilities to produce turbulence. When waves are reasonably linear (as opposed to, for example, strongly nonlinear solitons or bores), the rate of small-scale wave breaking is controlled by and equal to the rate at which energy is transferred from large to small-scale waves through wave-wave interactions. In the open ocean, theories

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have been developed that use concepts of wave-wave interaction to predict turbulent mixing rates in terms of larger-scale shear and stratification. Such theories, in particular the class known as Gregg-Henyey parameterizations, compare well to observed turbulent dissipation rates.

However, in the coastal ocean empirical evidence suggest that the Gregg-Henyey (GH) model fails to reproduce observed turbulence [*Kunze et al.*, 2002; *MacKinnon and Gregg*, 2003] . We plan to use an idealized numerical model of coastal internal waves to determine how to best represent and parameterize the relationship between turbulent mixing and shear from the internal waves that ultimately supply the energy for mixing. Using the pseudo-spectral model of *Winters et al.* [2004], we are able to explicitly resolve the cascade of energy from large to small-scale internal waves, and hope to understand why this cascade is different in coastal waters.

Specifically, the Gregg-Henyey theory predicts that the turbulent dissipation rate scales quadratically with the spectral energy level of the internal wave field,

$$\epsilon \propto \hat{E}^2.$$

However, coastal observations *MacKinnon and Gregg* [2003]; *Carter et al.* [2005] show dissipation to empirically scale with the magnitude of low-frequency shear, or equivalently with the square root of low-mode energy,

$$\epsilon_{\text{coast}} \propto \sqrt{E}.$$

Studies on the New England Shelf, Monterey Shelf, and Oregon Shelf (G. Avicola, OSU, pers. comm.) all show similar scaling, but with different coefficients. Thus far, there has not been a good theoretical basis for a different coastal turbulence scaling.

WORK COMPLETED and RESULTS

I started by trying to step back and understand as simple a case as possible, the decay of a single monochromatic internal wave. Simulations were performed with the pseudo-spectral model of *Winters et al.* [2004]. The run was initialized with a single monochromatic, relatively large scale internal wave and infinitesimal noise at all scales (Fig. 1, left). The domain is periodic in all directions. As the simulation evolves, nonlinear interactions transfer energy to smaller scales, untill a broadband spectrum is created in which continued tidal forcing is balanced by down-scale energy transfer and dissipation (Fig. 1). The broadband spectrum has wavenumber and frequency spectral slopes close to -2, consistent with the empirical Garrett-Munk spectrum (Fig. 2).

To understand the nature of the downscale energy transfer, the technique of *Scott and Arbic* [2007] can be applied to explicitly calculate the spectral downscale energy flux:

$$\frac{\partial \hat{E}(k_z)}{\partial t} = \frac{\partial T(k_z)}{k_z}, \tag{1}$$

where $T(k_z)$ gives the rate of energy transfer through a given wavenumber k_z, by calculating all triad interactions with members on both sides of k_z. This method shows on bulk a convergent down-scale

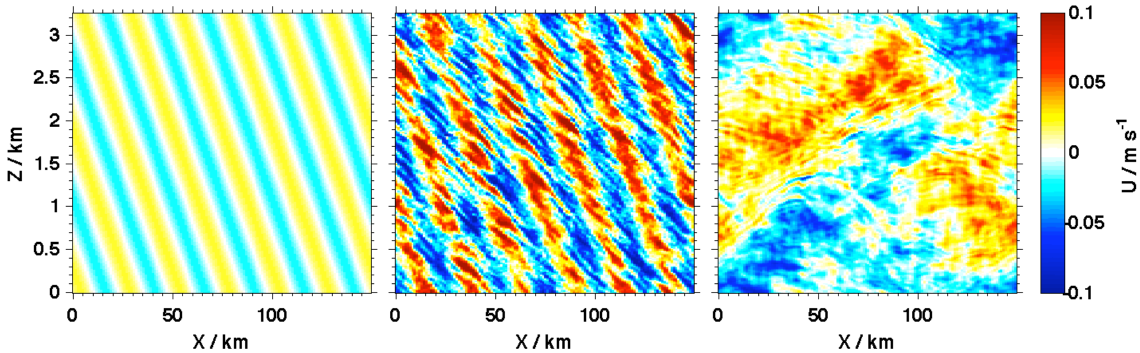

Figure 1: *Snapshots of evolving velocity field at three points in time, showing the transfer of energy towards smaller scales*

energy transfer in the spinup stage and steady down-scale energy transfer in steady state (Fig. 3). A detailed look at the triads involved shows that Energy gain at small scales is dominated by scale-separated interactions with low-mode waves [*Henyey et al.*, 1986].

One of the leading hypotheses for why the dissipation rate scaling is different in a coastal environment is that the coastal ocean is highly variable in time, and the internal wave-field never achieves the type of steady state that underlies previous theories [*MacKinnon and Gregg*, 2003]. To test this hypothesis a series of simulations were first run to steady state with different levels of wave forcing (Fig. 4 black lines/dots). The resultant dissipation rate scales **quadratically** ($\epsilon \propto \hat{E}^2$), in agreement with numerous previous theories and simulations [*Winters and D'Asaro*, 1997].

Next, after the fifth simulation reached a steady-state the wavenumber and phase of the forcing tide was abruptly changed and the evolution studied over the subsequent 20 days. During the first 10 days, energy is added to a new low-mode tide, but the higher-mode waves are not yet in balance with the low-mode energy (Fig. 4, left panel). During this 'evolution' period, the dissipation rate increases **slowly** with increasing energy ($\epsilon \propto \sqrt{E}$). This is the same scaling observed by MacKinnon and Gregg, perhaps because in coastal areas internal tides are highly variable and the wavefield is never in steady state.

RELATED PROJECTS

For the IWISE experiment I am conducting a series of numerical simulations of internal tides interacting with a mean sheared flow. For that experiment the goal is to understand how a mean current like the Kuroshio affects the generation and propagation of internal tides through refraction or wave breaking. As their are also mean sheared flows in coastal environments, especially at the shelf-break, these results may be applicable in a wide range of situations.

IMPACT / APPLICATIONS

Accurate representation or parameterization of turbulence from breaking internal waves is necessary for regional and larger-scale numerical models to successfully reproduce the evolution of regional currents,

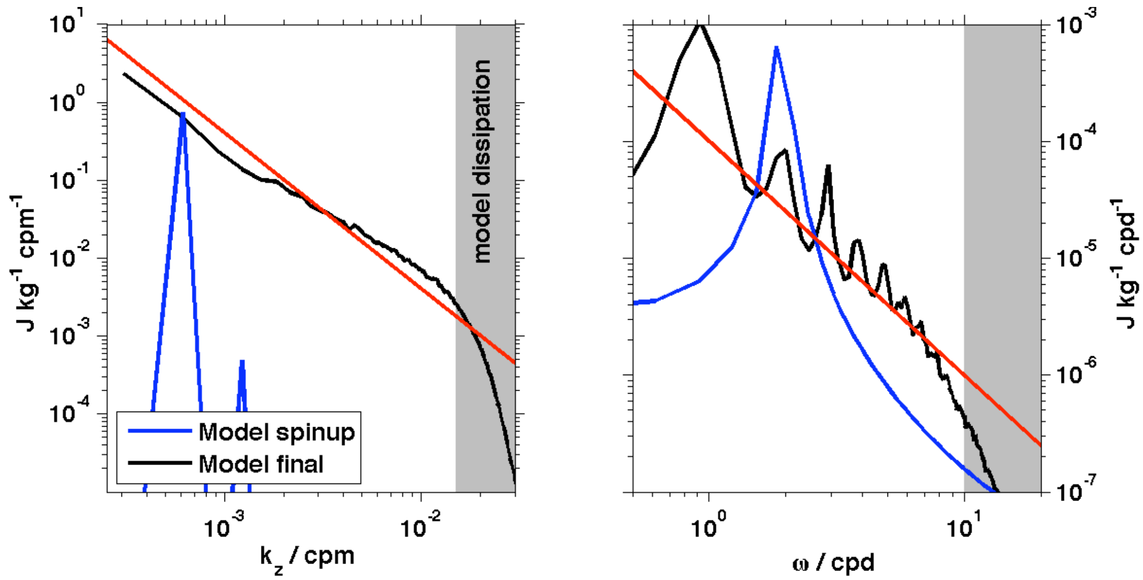

Figure 2: *Early and late vertical wavenumber (left) and frequency (right) energy spectra, showing the filling out of a stead-state Garrett-Munk like spectrum.*

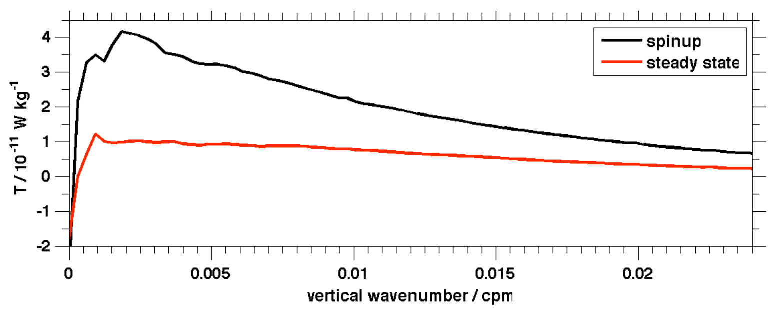

Figure 3: *Downscale transfer rates as a function of vertical wavenumber.*

water properties, and particulate matter distribution on timescales of weeks to months. This work attempts to understand the dynamics leading from internal waves to turbulence and develop parameterizations that can be used in regional numerical models. A further expected outcome of this analysis will be a demarcation of which parameterization is appropriate for different model resolutions.

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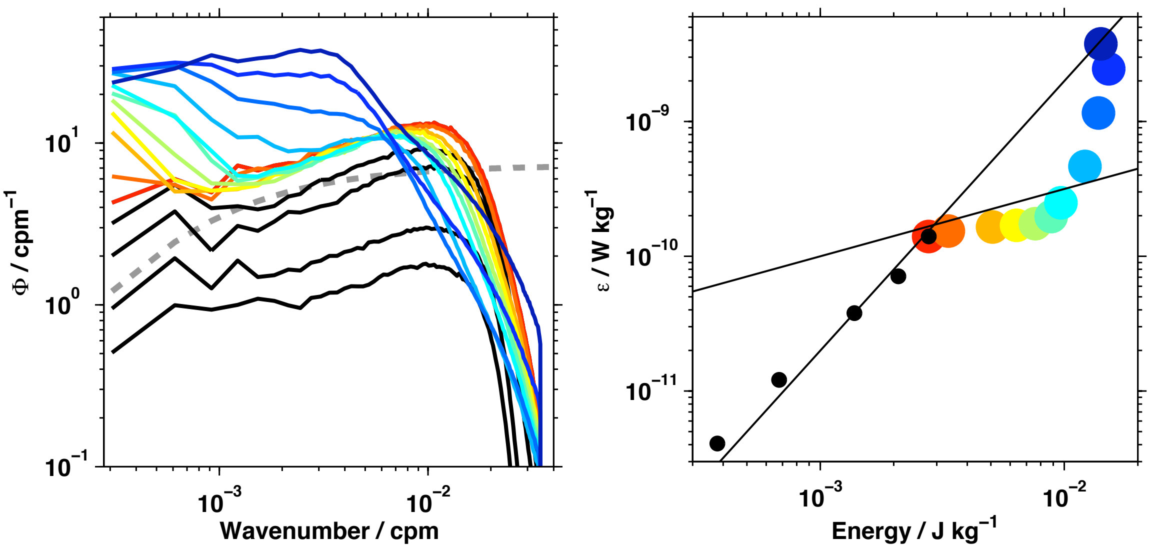

Figure 4: *Wavenumber spectra (left) and dissipation rate (right) are shown for 5 simulations run to steady state with different levels of wave forcing (black lines/dots). For the fifth simulation, the wavenumber and phase of the forcing tide is abrubtly changed, and the evolution over 20 days is shown in color (red to blue).*

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